Effects of planting density on tree growth and induced soil suction

Ng, C. W. W.; Ni, J. J.; Leung, A. K.; Zhou, C.; Wang, Z. J.

Published in:
Géotechnique

DOI:
10.1680/jgeot.15.P.196

Publication date:
2016

Ng, C. W. W. *et al. Géotechnique* [http://dx.doi.org/10.1680/jgeot.15.P.196]

Effects of planting density on tree growth and induced soil suction

C. W. W. NG*, J. J. NI*, A. K. LEUNG†, C. ZHOU* and Z. J. WANG*

Plant evapotranspiration is recognised to affect soil suction of slopes and landfill covers. Previous work has focused on evapotranspiration-induced suction by a single plant, with little attention paid to the effects of planting density. The aim of this study is to quantify any changes in tree growth and tree-induced suction during evapotranspiration and rainfall under different planting densities for non-mixed-species plantations. A tree species, *Schefflera heptaphylla*, which is commonly found in Asia, was planted in silty sand at spacings of 60, 120 and 180 mm, representing three different planting densities. For each case, three replicates were tested to consider tree variability. In total, the responses of suction for 297 seedlings subjected to drying and a rainfall event with a 10-year return period were measured. The test results show that reducing the tree spacing from 180 to 60 mm induced greater tree–tree competition for water, as indicated by a 364% increase in peak suction upon evapotranspiration. Such tree–tree interaction led to: (*a*) a 19–35% reduction in the leaf area index; (*b*) a 17–36% decrease in root length; and (*c*) an obvious decay of roots. Upon the rainfall event, the infiltration rate for vegetated soil with trees planted at a spacing of 60 mm was up to 247% higher than those for soil with a wider tree spacing, where mainly fresh roots were found. Although most suction within the root zone (i.e. top 100 mm) was lost due to increased infiltration at 60 mm spacing, suctions in deeper depths below root zone were largely preserved.

KEYWORDS: laboratory tests; partial saturation; suction; vegetation

INTRODUCTION

The presence of vegetation and its evapotranspiration has been recognised to affect the hydrology of the vadose zone of some civil engineering systems, such as embankments, slopes and landfill covers (Scanlon *et al.*, 2005; Smethurst *et al.*, 2006, 2015; Leung & Ng, 2013; Sinnathamby *et al.*, 2013). Plant evapotranspiration could directly affect the magnitude and distribution of moisture content and suction in the vadose zone. Such evapotranspiration-induced increase in suction could result in a reduction in soil hydraulic conductivity and an increase in shear strength (Ng & Menzies, 2007; Ng & Leung, 2012), increasing the stability of civil engineering systems, especially under rainfall conditions.

Improved ecological restoration of civil engineering systems including man-made or engineered slopes and landfill covers requires knowledge of an optimised planting density. By knowing an optimised plant arrangement, the aim is to minimise unfavourable plant–plant competition, so as to encourage plant growth and, hence, potentially maximise the beneficial effects of evapotranspiration-induced suction on the stability of these systems. Using a small plant spacing (or high planting density) has been shown to discourage plant growth and hence reduce plant biomass (both above ground and below ground) and crop yield (Azam-Ali *et al.*, 1984; Darawsheh *et al.*, 2009), because of increased competition for water, nutrients and light from neighbouring plants (Green *et al.*, 2001; Benomar *et al.*, 2012). The recommendations for plant spacing (e.g. approximately 0·5 m; GEO, 2011) provided in existing guidelines for the restoration of slopes are, however, empirically based and are made primarily from the practical and aesthetic point of view.

Although studies have been conducted to quantify evapotranspiration-induced suction by a single plant (Fatahi *et al.*, 2010; Garg *et al.*, 2015a; Leung *et al.*, 2015b), seldom have the effects of planting density on suction responses in the vadose zone been investigated. Different plant spacings would result in different degrees of overlap among root systems, and hence different influence zones of induced suction. Also not well understood is how different degrees of plant–plant interaction due to different planting densities would affect the growth of the root system, which has been shown to have a significant impact on the water uptake ability of roots (López *et al.*, 2001; Garg *et al.*, 2015a) and water retention behaviour (Grayston *et al.*, 1997; Traoré *et al.*, 2000; Scanlan & Hinz, 2010; Scholl *et al.*, 2014; Leung *et al.*, 2015a, 2015b; Ng *et al.*, 2016).

The present study investigated the effects of planting density on plant growth and its influence on the magnitude and distribution of suction affected by evapotranspiration and rainfall. A tree species, *Schefflera heptaphylla*, was selected for testing. Three different planting densities were considered. For each density, three replicates of the same tree species were tested to take into account any differences of the properties of seedlings supplied from a nursery, including tree height and the size of root system. Effects of planting density on tree characteristics including leaf area index (LAI) and root area index (RAI) as well as soil water retention behaviour were investigated. These soil and tree properties were then used to interpret the suction responses upon evapotranspiration and rainfall. It should be noted that mixed-species planting of tree and grass conditions are beyond the scope of this study.

TEST PLAN

In total, ten tests were conducted – nine for vegetated soil considering different planting densities and one for bare soil (control; test B). Three planting densities, 320, 81 and 36 tree seedlings/m^2, were examined, corresponding to the plant

Manuscript received 3 September 2015; revised manuscript accepted 3 March 2016.
Discussion on this paper is welcomed by the editor.
* Department of Civil and Environmental Engineering, Hong Kong University of Science and Technology, Clear Water Bay, Kowloon, Hong Kong.
† School of Science and Engineering, University of Dundee, Nethergate, Scotland, UK.

spacings of 60 mm (test S60), 120 mm (test S120) and 180 mm (test S180), respectively. These plant spacings are equivalent to one, two and three times the maximum lateral spread of plant roots, as supplied from a nursery. In order to consider the effects of any differences of the properties of seedlings on test results, three replicates were tested for each planting density in tests S60_1, S60_2, S60_3, S120_1, S120_2, S120_3, S180_1, S180_2 and S180_3.

TEST SET-UP AND INSTRUMENTATION

Ten big test drums were constructed, each with a diameter of 600 mm and a height of 500 mm (Fig. 1). Soil was compacted in each drum to a depth of 450 mm. Multiple holes, each with a diameter of 5 mm, were made in the bottom of the drums to create a free drainage boundary condition and to collect any water percolated from the base during rainfall. Any surface runoff generated by an applied rainfall event was allowed and was collected by an overflow channel at the same elevation as the soil surface on each drum (see Fig. 1). To facilitate the runoff process, the soil surface was inclined at a small angle of less than 2° towards the channel. Therefore, no surface ponding was allowed in any of the tests. All drums were placed in a temperature- and humidity-controlled plant room during the testing period. The daily temperature and relative humidity in the room were maintained constant at 25 ± 1°C and 60 ± 5%, respectively. The light intensity provided by the cool white fluorescent

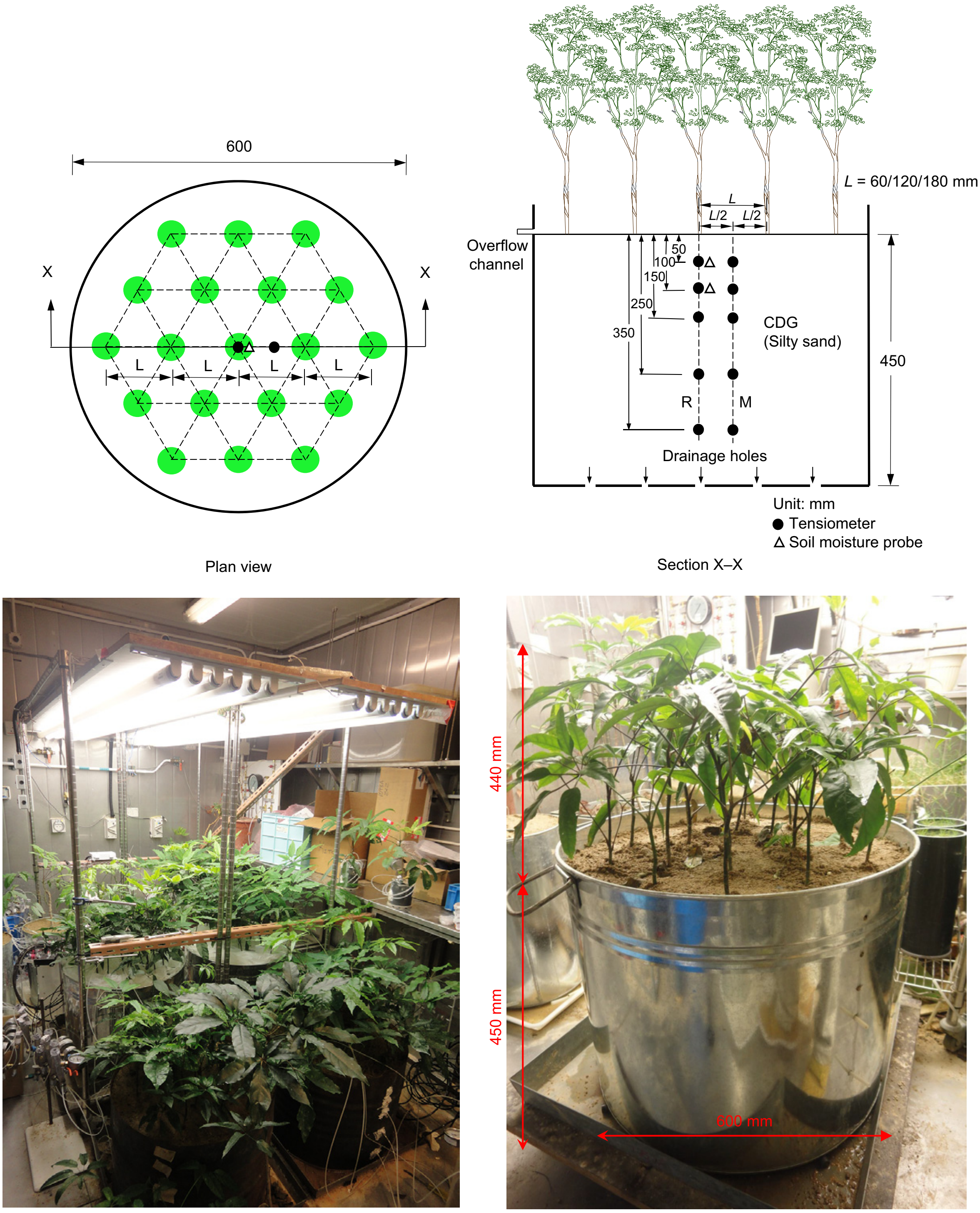

Fig. 1. Schematic diagrams and pictures of the test set-up and instrumentation in the temperature- and humidity-controlled plant room

lamp that was placed on the top of each drum was controlled to approximately 120 (μmol/m^2)/s within the 400–700 nm waveband (i.e. equivalent to 5·0 (MJ/m^2)/day). This particular range of waves is known to be favourable for plant photosynthesis and plant growth (Gates, 1980; Ng *et al.*, 2014). Based on the atmospheric condition in the plant room, it can be estimated from the Penman equation (Penman, 1948) and Penman–Monteith equation (Allen *et al.*, 1998) that the potential evaporation (PE) and potential evapotranspiration (PET) were 4·46 and 2·51 mm/day, respectively.

In order to measure the responses of negative pore-water pressure (PWP) or suction, two vertical arrays of miniature-tip tensiometers (2100F, Soil Moisture Equipment Cooperation) were installed along the drum depth (see Fig. 1). One array, denoted by R and consisting of five tensiometers, was installed directly beneath a tree seedling located in the middle of the drum to prevent any boundary effects on measurements. The instrument depths were 50, 100, 150, 250 and 350 mm. Another array, denoted by M, was installed next to array R at a distance equal to half of the plant spacing being considered. Owing to the possibility of water cavitation, the maximum suction that could be recorded by each tensiometer was 90 kPa. Two soil moisture probes (SM300; Delta-T Device Ltd) were installed at depths of 50 and 100 mm right next to the two tensiometers to monitor the volumetric water content (VWC). The purposes of installing moisture probes were to check the measurements of suction against those of VWC and also to investigate the effects of root and plant spacing on soil water retention behaviour. Each moisture probe was calibrated in the laboratory and the accuracy was found to be ± 3% of VWC.

In order to simulate different rainfall patterns in terms of intensity and duration, a rainfall device similar to that developed by Ng *et al.* (2014) was developed. The device consisted of 12 horizontal plastic tubes that were connected to a water source. The plastic tubes had small holes each with a diameter of 1 mm for discharging water in the form of droplets uniformly over the entire drum surface. A flow meter with an accuracy of ± 0·5 l/h was attached to the rainfall device so that any desired water discharge rate (i.e. rainfall intensity) and discharge duration (i.e. rainfall duration) can be applied during testing.

SOIL TYPE AND SAMPLE PREPARATION METHOD

The type of soil tested in this study was completely decomposed granite (CDG), which is commonly found in tropical and sub-tropical regions of the world such as Hong Kong. Measurements of the particle-size distribution show that the contents of gravel, sand, silt and clay in the CDG were 19, 42, 27 and 12%, respectively. The plastic limit and liquid limit of CDG are 26 and 44%, respectively. According to the Unified Soil Classification System (USCS; ASTM, 2010), CDG can be classified as silty sand. Based on the results from standard Proctor tests, the maximum dry density and the corresponding optimum water content (by mass) of the CDG are 1870 kg/m^3 and 12%, respectively. Other measured index properties of the CDG are summarised in Table 1.

The CDG in each test drum was compacted by moisture tamping at a relative compaction (RC) of 95% (corresponding to the dry density of 1777 kg/m^3). Compacting to such a high RC is common for man-made slope design against rainfall infiltration and its induced slope instability in some countries, including the USA (TDOT, 1981) and Hong Kong (GCO, 2000). Various experiments have shown that the species selected in this study, *S. heptaphylla*, is able to survive and thrive under this level of compaction (Garg *et al.*, 2015a, 2015b; Leung *et al.*, 2015a, 2015b). CDG has a field capacity of 21%, which is defined as the water content held in soil after excess water has drained away, assuming a negligible rate of water movement (Veihmeyer & Hendrickson, 1931). This water content corresponds to soil suction of 25 kPa. Leung *et al.* (2015a) reported that the saturated hydraulic conductivity k_s of CDG at an RC of 95% was $1{\cdot}2 \times 10^{-8}$ m/s. In each drum, the CDG was compacted in 15 layers, with each spanning a height of 30 mm. Between each successive layer, the soil surface was scarified to provide better contact.

Table 1. Index properties of completely decomposed granite (CDG)

Index properties	Value
Standard compaction tests	
Maximum dry density: kg/m^3	1870
Optimum moisture content: %	12
Particle-size distribution	
Gravel content (>2 mm): %	19
Sand content (≤2 mm): %	42
Silt content (≤63 μm): %	27
Clay content (≤2 μm): %	12
D_{10}: mm	0·15
D_{30}: mm	0·7
D_{60}: mm	2
Coefficient of uniformity (D_{60}/D_{10})	13·3
Coefficient of curvature ($(D_{30})^2/(D_{60}D_{10})$)	1·6
Specific gravity	2·60
Atterberg limit	
Plastic limit: %	26
Liquid limit: %	44
Plasticity index: %	18
Unified Soil Classification System (USCS)*	Silty sand (SM)

*ASTM (2010)

SELECTED PLANT SPECIES AND GROWTH CONDITION

The plant species investigated in this study was *S. heptaphylla*, which has sharp leaves and is common in many parts of Asia including southern China, Japan, Vietnam and India (Hau & Corlett, 2003). *S. heptaphylla* is a small tree species. This species is selected for testing because it has significant ornamental and ecological value for slope rehabilitation and reforestation (GEO, 2011) and is drought tolerant (Hau & Corlett, 2003).

In total, 61, 25 and 13 seedlings of *S. heptaphylla* were transplanted to the test drums with uniform tree spacings of 60 mm (test S60), 120 mm (test S120) and 180 mm (test S180; Fig. 1), respectively. All 297 seedlings tested in this study (single plant species) were grown in a nursery under identical soil and environmental conditions and thus they have similar tree properties, including the maximum lateral root spread with an average value of 60 mm. For tests involving the tree spacing of 60 mm, the tree roots sat right next to each other without overlapping. The distances between the tree seedlings in tests S120 and S180 were approximately two and three times the maximum lateral spread of the tree roots (i.e. ~60 mm), respectively, as planted. For a fair comparison, tree seedlings with similar heights, basal diameters and root depths were selected for testing. The mean basal diameter (i.e. the diameter of the stem at the base of a tree) was 6 ± 2 mm. Table 2 shows the range, mean and standard deviation of these properties for all selected tree seedlings involved in the nine tests.

Table 2. Summary of tree characteristics

Tree characteristics	S60			S120			S180		
	S60_1	S60_2	S60_3	S120_1	S120_2	S120_3	S180_1	S180_2	S180_3
After transplantation									
Height: mm	425–451 Mean: 440 S.D.: ±10	412–458 Mean: 436 S.D.: ±16	413–481 Mean: 449 S.D.: ±26	423–461 Mean: 438 S.D.: ±15	416–469 Mean: 443 S.D.: ±21	421–481 Mean: 443 S.D.: ±23	424–458 Mean: 435 S.D.: ±13	428–469 Mean: 445 S.D.: ±16	412–476 Mean: 442 S.D.: ±27
Leaf area index (LAI)	0·55–0·84 Mean: 0·70 S.D.: ±0·10	0·62–0·75 Mean: 0·68 S.D.: ±0·06	0·48–0·86 Mean: 0·71 S.D.: ±0·13	0·52–0·89 Mean: 0·68 S.D.: ±0·14	0·46–0·82 Mean: 0·65 S.D.: ±0·14	0·45–0·83 Mean: 0·64 S.D.: ±0·15	0·58–0·82 Mean: 0·68 S.D.: 0·09	0·54–0·83 Mean: 0·66 S.D.: 0·10	0·58–0·82 Mean: 0·72 S.D.: 0·11
Root depth: mm	65–89 Mean: 78 S.D.: ±10	75–92 Mean: 84 S.D.: ±8	54–95 Mean: 74 S.D.: ±16	66–92 Mean: 81 S.D.: ±12	72–98 Mean: 85 S.D.: ±11	72–94 Mean: 84 S.D.: ±9	71–93 Mean: 82 S.D.: ±9	68–98 Mean: 80 S.D.: ±13	69–98 Mean: 87 S.D.: ±12
After 4 months of growth									
Height: mm	501–601 Mean: 564 S.D.: ±39	512–663 Mean: 583 S.D.: ±68	523–689 Mean: 586 S.D.: ±32	565–663 Mean: 600 S.D.: ±48	485–576 Mean: 544 S.D.: ±39	513–645 Mean: 572 S.D.: ±52	526–689 Mean: 584 S.D.: ±63	567–613 Mean: 575 S.D.: ±24	523–616 Mean: 560 S.D.: ±36
Leaf area index (LAI)	0·84–0·97 Mean: 0·91 S.D.: ±0·05	0·59–1·12 Mean: 1·02 S.D.: ±0·09	0·82–1·06 Mean: 0·95 S.D.: ±0·10	1·03–1·16 Mean: 1·10 S.D.: ±0·04	1·02–1·24 Mean: 1·12 S.D.: ±0·08	1·08–1·43 Mean: 1·20 S.D.: ±0·14	1·25–1·47 Mean: 1·35 S.D.: ±0·11	1·12–1·34 Mean: 1·26 S.D.: ±0·09	1·23–1·52 Mean: 1·40 S.D.: ±0·11
Root depth: mm	101–128 Mean: 118 S.D.: ±10	108–143 Mean: 126 S.D.: ±14	120–157 Mean: 137 S.D.: ±13	131–164 Mean: 146 S.D.: ±13	126–158 Mean: 145 S.D.: ±12	134–161 Mean: 148 S.D.: ±10	142–185 Mean: 160 S.D.: ±18	117–174 Mean: 147 S.D.: ±19	148–181 Mean: 165 S.D.: ±12
Peak root area index (RAI)	0·56–0·79 Mean: 0·66 S.D.: ±0·10	0·72–0·78 Mean: 0·75 S.D.: ±0·04	0·61–0·82 Mean: 0·68 S.D.: ±0·09	0·54–0·66 Mean: 0·61 S.D.: ±0·05	0·62–0·70 Mean: 0·65 S.D.: ±0·05	0·49–0·64 Mean: 0·54 S.D.: ±0·06	0·62–0·46 Mean: 0·53 S.D.: ±0·07	0·55–0·67 Mean: 0·60 S.D.: ±0·06	0·39–0·60 Mean: 0·48 S.D.: ±0·09

After transplantation, all seedlings were grown for 4 months in the plant room and watered every 3 days so that the average soil moisture was maintained close to the field capacity of the soil. The growth duration and the applied irrigation schedule are considered to be favourable and sufficient for root establishment (Wang *et al*., 2007) before testing commenced. No fertiliser was added during the growth period to prevent any induced osmotic suction caused by solutes in the soil pore water (Krahn & Fredlund, 1972). During the growth period, any change in LAI was monitored for all tree seedlings. LAI is a dimensionless index for a single plant and it is defined as the ratio of the total leaf area to the projected area of canopy of an individual plant on the soil surface in horizontal plane (Watson, 1947). LAI was determined by image analysis using an open source software called ImageJ (Rasband, 2011). Images of individual tree leaves were captured by a high-resolution camera and then converted to binary images, based on which the leaf area can be determined.

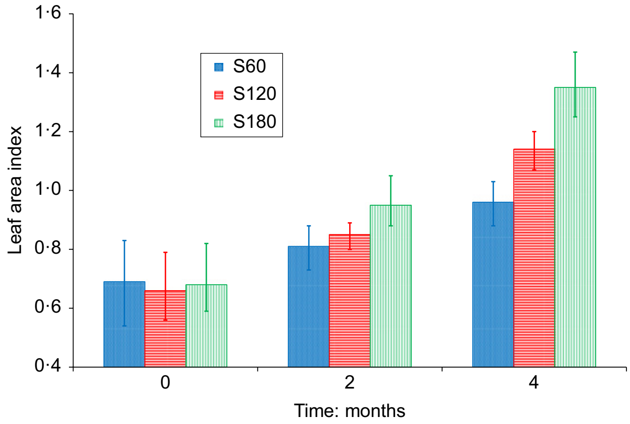

Fig. 2. Observed changes in LAI during the growth period under different planting densities

TEST PROCEDURES

After growing for 4 months, the seedlings in the drums were subjected to a two-stage test. The first stage was designed to study the effects of planting density on the magnitude and distribution of suction induced by evapotranspiration. Before evapotranspiration, the soil surface of each drum was ponded until (*a*) the readings of all tensiometers reduced to zero; (*b*) all soil moisture probes recorded saturated VWC; and (*c*) percolation from the bottom drainage holes was observed. This procedure was aimed at establishing a similar initial hydraulic condition so that the responses of PWP and VWC in the subsequent stages were comparable. Thereafter, the soil surface of all drums was exposed to the same, constant atmospheric conditions in the plant room for evaporation (test B) and evapotranspiration (tests S60, S120 and S180) for 4 days. The holes in the bottom of the drums remained open for free drainage during testing. Variations in suctions and VWC were monitored throughout the tests.

Immediately after the 4-day evaporation and evapotranspiration, the second stage of testing commenced. All seedlings in the drums were subjected to a rainfall event simulated using the rainfall device. A constant rainfall intensity of 73 mm/h was applied and maintained for 2 h. According to a statistical study of 100 years of rainfall data in Hong Kong (Lam & Leung, 1995), the applied rainfall pattern is equivalent to a 10-year return period (i.e. a typical design return period for the stability of man-made slopes in Hong Kong). During the rainfall period, the responses of suction, VWC, any surface runoff and basal percolation were recorded. Any rainfall interception by tree leaves was also determined. Four cups each with a diameter of 70 mm were placed uniformly on the soil surface of each test drum to collect any rainwater that was not intercepted. It was found that only 4–6% of the applied rainfall was intercepted during the first 5 min of rainfall and, thereafter, no interception was observed. Since the amount of rainfall intercepted was negligible, the infiltration rate can be determined by subtracting any surface runoff from the applied rainfall intensity.

Once the two-stage test was completed, the root area index (RAI) of all tree seedlings was determined. RAI is defined as the ratio of total root surface area for a given depth range to the circular cross-sectional area of soil in the horizontal plane (Francour & Semroud, 1992). The circular cross-sectional area of soil refers to the circular area, of which the diameter is defined by the maximum lateral spread of the root system within a given depth range. The root surface area refers to the total outside (external) surface area of all roots within a given soil volume that is defined by the cross-sectional area and the depth range. RAI is a dimensionless index that indicates the water uptake ability of roots within the root zone. The tree roots were carefully removed from the test drums and the soil attached to the roots was washed away with great care according to the standardised root washing procedures adopted by Smucker *et al*. (1982). Using the principle of hydropneumatic elutriation, roots were separated from compacted soils in an attempt to minimise the destruction of small lateral roots and other fragile root structures. During root excavation, root depth was determined as the deepest soil depth beyond which no root was found. Then, image analysis using ImageJ (Rasband, 2011) was conducted to determine RAI, following the procedures suggested by Garg *et al*. (2015a). High-resolution images were taken 360° around the roots. All these images were combined to generate a three-dimensional (3D) image. Grids with equal pixel size (i.e. 12 pixels per unit mm of length) were superimposed on the 3D image. The total number of grids that contain roots at the given depth range was counted and hence converted into the total outside surface area of roots in mm^2. Finally, RAI at any depth within a root zone can be determined by dividing the total outside surface area of roots at a given depth by the planar cross-sectional area of soil.

INTERPRETATION OF TEST RESULTS

Effects of planting density on plant characteristics

Figure 2 shows the measured variation in tree LAI during the growth period. Based on the test results, it is the behaviour of the selected species, *S. heptaphylla*, to grow in an approximately linear rate with time at a relatively young stage. Seedlings grown at a lower planting density (or larger spacing) experienced a larger increase in LAI than seedlings grown at a higher density (or smaller spacing). After growing for 4 months, the seedlings tested in S180 had LAIs that almost doubled from $0{\cdot}68 \pm 0{\cdot}10$ to $1{\cdot}35 \pm 0{\cdot}11$, whereas those tested in S60 had LAIs that increased by approximately 36% only. Such an effect of planting density on LAI is consistent with the findings for eucalyptus species (Pinkard & Neilsen, 2003) and cotton crops (Darawsheh *et al*., 2009). These trends are likely because the lateral growth of leaves under a higher planting density was suppressed to a greater extent as more leaves were shaded by adjacent plants (Fig. 1). Shading reduced photosynthesis, and hence leaf growth. Table 2 summarises the characteristics of each replicate before and after the growth period.

Fig. 3. Roots of tree replicates planted at different planting densities excavated after testing (the sheet of paper in the background contains 10 mm × 10 mm squares): (a) S60_1; (b) S120_1; (c) S180_1; (d) S60_2; (e) S120_2; (f) S180_2; (g) S60_3; (h) S120_3; (i) S180_3

Figure 3 compares the typical root geometry of some tree seedlings grown at the three planting densities after testing. In general, the roots of tree seedlings from test S60 and its replicates were shorter and more localised. Some of the roots had decayed. On the contrary, the roots of seedlings from test S180 were longer and more dispersed. The roots were mainly fresh (displaying a whitish colour) and were 17–36% longer than those in test S60 (Table 2). With little lateral and vertical extension, the total root volume in tests S60 was only one-third of that in tests S180. Fig. 4 shows that the distributions of RAI are non-linear and parabolic in shape in all cases. RAI peaked at depths of 60–90 mm. Interestingly, even though seedlings in tests S60 had smaller root volumes than those in test S180 (Fig. 3), the peak RAI within 10–90 mm depth was around 34% higher (Fig. 4). However, the peak RAI values in tests S60 are around 70% less than those measured by Garg *et al.* (2015a), who used the same plant species and similar soil types. This is because the tree seedlings investigated by Garg *et al.* (2015a) allowed for a longer period of growing time (8 months) than those in this study (4 months) under the same laboratory environment.

At a higher planting density, the demand and competition for water would be greater among neighbouring seedlings. The greater consumption and depletion of soil moisture

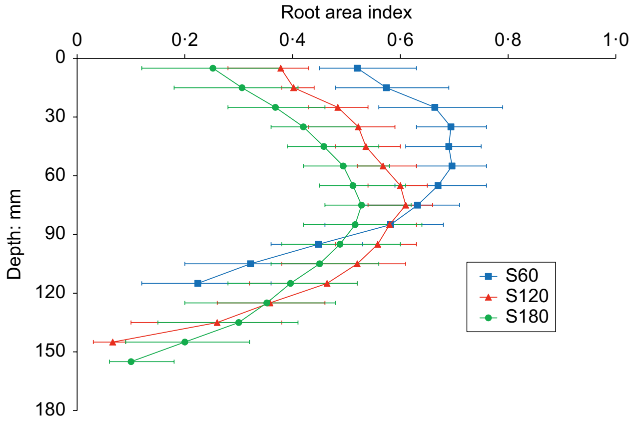

Fig. 4. Effects of planting density on RAI after a 4-month growth period

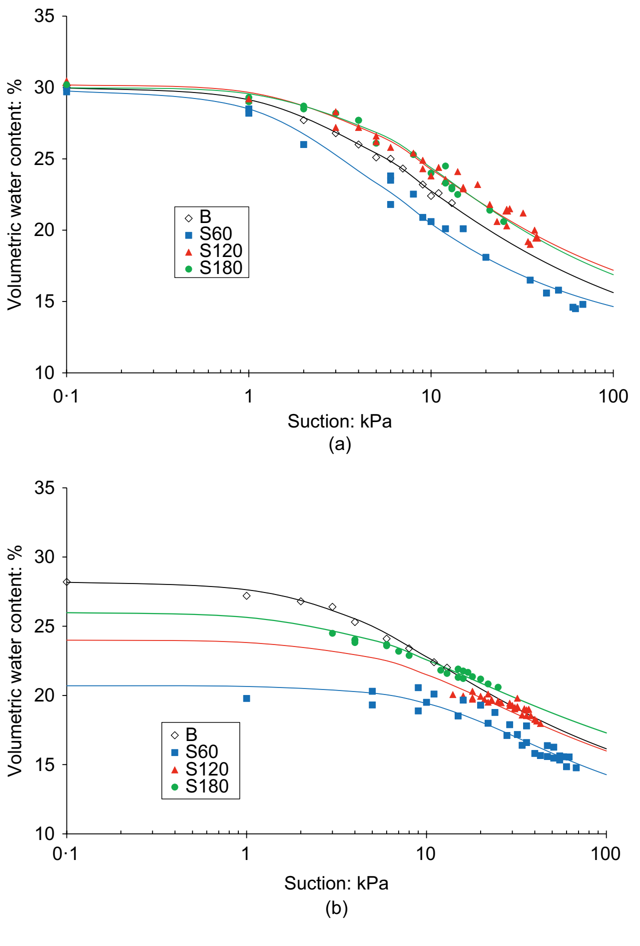

Fig. 5. Comparisons of measured SWRCs of bare soil and vegetated soil along (a) the drying path and (b) the wetting path

would lead to a substantial reduction in root activity (Casper & Jackson, 1997; Jiang *et al.*, 2013). This explains why the root growth for all seedlings was much more localised in test S60 than in test S180 where seedling competition was less intense (Fig. 3). However, owing to the water stress associated with the tree–tree competition, plants would in general activate abscisic acid for root proliferation (hence increase RAI; Fig. 4) and survival (Munns & Sharp, 1993). Similarly to the laboratory observation, the root volume of mature plants in the field also increases when root density decreases at wider plant spacing (Eastham *et al.*, 1990; Hunter, 1998).

Effects of roots on the water retention ability of soil

Figure 5(a) shows the drying path of the soil water retention curve (SWRC) of bare soil and vegetated soil with seedlings planted at the three planting densities. The SWRCs were obtained by relating the measured VWC to suction at a depth of 50 mm during the 4-day evaporation (for bare soil) and evapotranspiration (for vegetated soil). Data points of SWRCs were from all the three replicates. The equation proposed by van Genuchten (1980) was used to fit the SWRCs. All required fitting parameters are shown in Table 3. The water retention ability of rooted soil was different from that of bare soil, and the difference appears to be dependent upon the planting density. For any given suction, the rooted soils in tests S120 and S180 had noticeably greater water retention ability than the bare soil. The presence of roots increased the air-entry value (AEV) of the soil from 2 to 4 kPa. Such enhanced water retention ability and increased AEV due to the presence of roots were also observed by Leung *et al.* (2015b), who tested the same soil type and tree species as in the present study but considered one single seedling only. Scanlan & Hinz (2010) proposed a conceptual model suggesting that, for a given soil water content, root occupancy in soil pore space could reduce the diameter of the soil pore throat, which in turn increases suction according to the capillary law. In addition, other biological factors such as the release of root exudates or organic acid (Grayston *et al.*, 1997; Traoré *et al.*, 2000) could alter the soil structure. Even though such bio-chemical root activity took place mainly within 2 mm away from the root surface (i.e. rhizosphere; Norton *et al.*, 1990; Sauer *et al.*, 2006), it may also contribute to an increase in the water retention ability of soil (Albalasmeh, 2013).

Interestingly, the rooted soil in test S60 showed reduced, rather than enhanced, water retention ability, as compared to the bare soil. The AEV decreased from 2 to 1 kPa, which is against the trend observed in the previous two cases (where planting densities were lower) and is inconsistent with the conceptual model proposed by Scanlan & Hinz (2010). The observed difference in water retention behaviour may be attributed to the decay of roots exclusively in test S60 and all its replicates (Fig. 3). Based on the observation made from the 183 tree seedlings investigated, decayed roots were always identified in soils with close tree spacing of 60 mm. This is consistent with the findings reported by Goldberg & Miller (1990), who reported that the occurrence of root decay is expected for densely spaced plants due to the intense competition among neighbouring plants. Root decay due to the significant tree–tree competition in this case might have created macro-pores in the soil (Ghestem *et al.*, 2011), which would reduce the water-holding ability of the soil, outweighing any effects of root occupancy. The observed reduction in AEV might be also attributed to the micro-fracturing of the soil associated with excessive root growth induced by the relatively significant tree–tree competition. The good agreement between the measured and fitted SWRCs suggest that the fitting equation proposed by van Genuchten (1980) is still applicable to soil with the presence of macropores (i.e. for S60 samples, where root decay was identified), unlike the suggestion made by Beven & Germann (2013).

Planting density also had noticeable effects on wetting SWRCs (i.e. those SWRCs obtained during rainfall), as shown in Fig. 5(b). It can be seen that the three vegetated soil samples had similar adsorption rates (i.e. increase in VWC for a given decrease in suction), but these rates were lower than that of the bare soil. Because of the hydraulic hysteresis, the wetting curve of both the bare and rooted soils did not follow the corresponding drying curve. The hysteresis loop of rooted soils in test S60 was much larger than those of the

Table 3. Summary of fitting parameters for van Genuchten (1980) equation

Test	Drying SWRC					Wetting SWRC				
	θ_s: m^3/m^3	θ_r: m^3/m^3	α: m^{-1}	n	m	θ_s: m^3/m^3	θ_r: m^3/m^3	α: m^{-1}	n	m
B	0·30	0·10	2·80	1·38	0·28	0·21	0·10	2·20	1·35	0·26
S60	0·29	0·10	4·00	1·50	0·33	0·24	0·10	0·60	1·50	0·33
S120	0·31	0·10	2·10	1·42	0·29	0·26	0·10	1·10	1·35	0·26
S180	0·30	0·10	1·80	1·45	0·31	0·28	0·10	1·80	1·27	0·21

other two rooted soil samples and the bare soil. This might be another indication that macro-pores had formed due to root decay, as the presence of macro-pores would lead to a more open soil structure. The resulting non-uniform distribution of soil pore size makes the so-called 'ink-bottle' effects in the soil more significant (Hillel, 1998).

Observed responses of evapotranspiration-induced suction and VWC

Figures 6(a) and 6(b) show the measured suction and VWC at a depth of 50 mm during the 4-day evaporation (for bare soil) and evapotranspiration (for vegetated soil), respectively. This particular depth of measurement was selected for investigation to correlate transpiration-induced suction with plant characteristics (in terms of RAI in this study) and hence to improve the understanding of soil–water–root interaction. As expected, the suction induced by evapotranspiration in the vegetated soil increased much more significantly, regardless of planting density, than the suction induced by evaporation in the bare soil (Fig. 6(a)). The peak evapotranspiration-induced suction at depth 50 mm in the vegetated soil was 64–425% higher than the peak evaporation-induced suction in the bare soil. The observed greater increase in suction in the vegetated soil was attributed to the greater reduction in VWC due to root water uptake (Fig. 6(b)). During the first 2 days of the drying period, only a slight difference in induced suction was observed among the three planting densities (Fig. 6(a)). However, as suction approached the field capacity (i.e. 25 kPa), the difference became much more significant. It is evident from Fig. 6 that the seedlings grown at a higher planting density consumed more water (i.e. the reduction in VWC was greater) during root water uptake, hence inducing higher suction. Beyond the field capacity (i.e. after 48 h), the average suction increment for test S60 (i.e. 51 kPa) was nearly four times (i.e. 364%) higher than that for test S180 (i.e. 11 kPa). This reflected the more intense tree–tree competition when seedlings were closer to each other. Some test results reported by Garg *et al.* (2015a), who measured evapotranspiration-induced suction by a single tree seedling, are also illustrated in the figure for direct comparison. The tree species, soil type and atmospheric condition in their study are identical to those in this study. The suction response in test S180 almost coincided with those reported by Garg *et al.* (2015a). This implies that the tree spacing of 180 mm allowed the seedlings plenty of room to grow and the suction responses were free from competition effects.

Figure 7 compares the responses of suction at greater depth of 250 mm (i.e. below the root zone) between the bare and vegetated soils. Similarly to the observation made in shallower depth of 50 mm (Fig. 6(a)), suction induced in all vegetated samples was higher than that in the bare sample and the amount of suction induced was higher when the plant spacing was closer. However, when compared to the

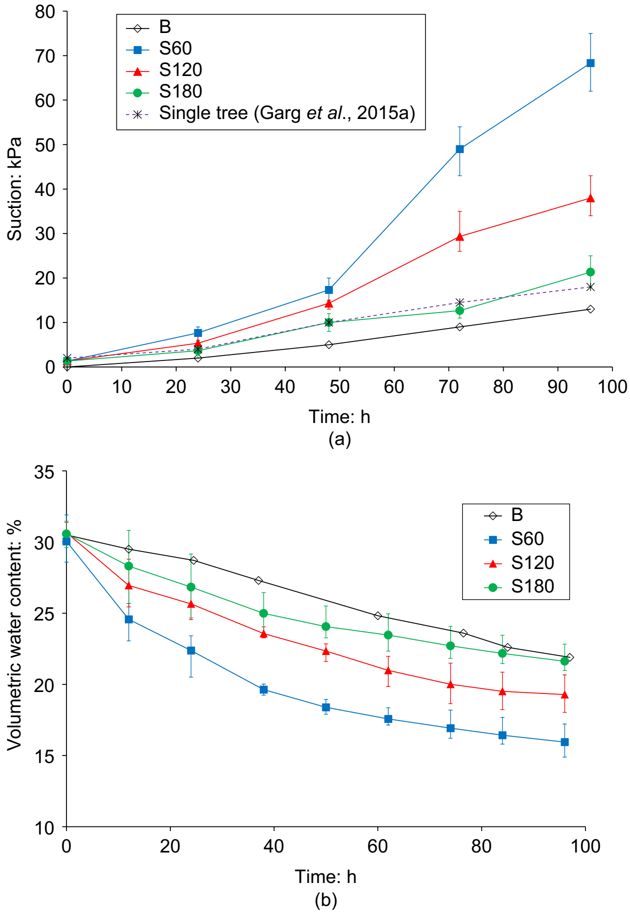

Fig. 6. Measured variations in (a) suction and (b) VWC with time at a depth of 50 mm during evaporation (bare soil) and evapotranspiration (vegetated soil)

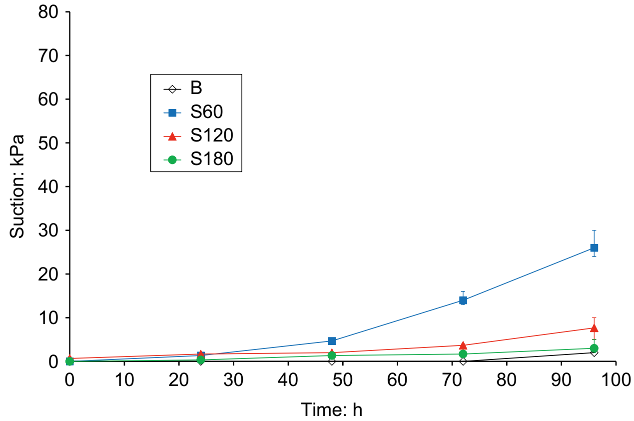

Fig. 7. Measured variations in suction with time at a depth of 250 mm during evaporation (bare soil) and evapotranspiration (vegetated soil)

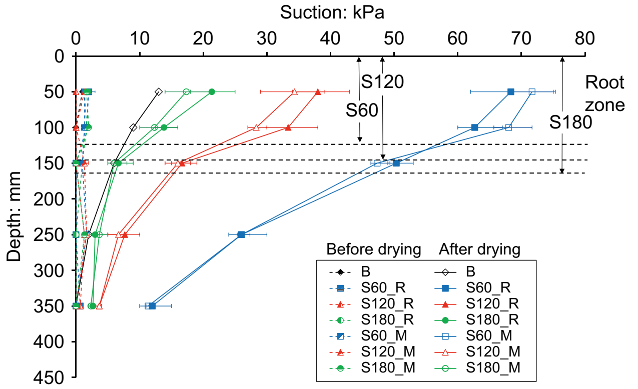

Fig. 8. Comparison of measured suction profiles between bare and vegetated soils along arrays M and R before and after drying

shallow depths, the magnitude of suction at greater depths was generally lower as they were measured at depths below the root zone and therefore were less influenced by root-water uptake that took place in the shallow root zone.

Figure 8 compares the vertical distributions of induced suction along the soil depth for the three planting densities. Evidently, tree seedlings spaced closer together induced a higher amount of suction at all depths for a given duration of evapotranspiration. Within the root zone, the amount of suction induced at a depth of 50 mm was always larger than that induced at a depth of 100 mm. In addition to the effects of surface evaporation, a major reason was the higher values of RAI at shallower depths (refer to Fig. 4), where root water uptake was likely to be greater (Garg *et al.*, 2015a). It is interesting to see that, even though the roots of the tree seedlings in test S60 were the shallowest among the three cases, their influence zone of induced suction was the deepest. This is likely to be because of the higher water demand associated with the tree–tree competition, which might have created a larger hydraulic gradient in the soil within and below the root zone. The continuous removal of soil moisture and the associated upward water flow caused soil drying at greater depths, extending the influence zone.

Figure 8 also compares the suction profiles induced along arrays M and R (see test set-up shown in Fig. 1). The main difference between results from these two arrays lies within the root zone. The tree seedlings having a wider spacing in both tests S120 and S180 induced higher levels of suction along array R than along array M. The opposite trend was observed in test S60. Although the root systems of the seedlings in tests S60 were initially situated next to each other without overlapping, post-test root excavation revealed that some roots eventually overlapped because of the 4 months of tree growth. Tree–tree competition for water in this overlapping root zone would be stronger (Farnham, 2001). This could explain why the levels of suction induced along array M were higher than those induced along array R only in test S60, but not in the other two tests where the tree roots did not overlap.

Effects of vegetation and planting density on infiltration rates

The measured infiltration rates for bare and vegetated soil during rainfall are shown in Fig. 9. As expected, the infiltration rate for the bare soil decreased exponentially with time, approaching a steady-state condition and k_s of the CDG (i.e. $1{\cdot}2 \times 10^{-8}$ m/s). The measurements show that the infiltration rate for vegetated soil may be higher or lower than that for bare soil depending on the planting density. When the tree spacing was 120 or 180 mm, the infiltration rate for vegetated soil was lower than that for bare soil by 18 to 58%. This trend appears to be consistent with the findings in past studies (Meek *et al.*, 1992; Ng *et al.*, 2014; Leung *et al.*, 2015a), which also showed that the infiltration rate for soil containing actively growing roots was reduced.

In contrast, when the trees were planted closer together (spacing = 60 mm), the infiltration rate for vegetated soil was 42–86% higher than that for bare soil in the present study. This might be attributed to the formation of preferential flow paths (hence a higher infiltration rate) as macro-pores were created in the soil due to the observed decay of roots (Ghestem *et al.*, 2011). In addition to the effects of decayed roots, planting density might also affect the infiltration rates because of (*a*) different stages of desaturation (i.e. as a result of transpiration-induced suction before rainfall happened; see Figs 6–8) and (*b*) different capacity of soil water storage. The test results obtained from the present study suggest that the infiltration rate for vegetated soil is not necessarily higher or lower than that for bare soil, as commonly claimed in past studies based on tests involving a single planting density only.

Observed suction responses during rainfall

Figure 10 compares the measured variations in suction with time at a depth of 50 mm (i.e. within the root zone) between the bare and vegetated soils during the 2-h rainfall. As expected, suction in all cases, with or without the presence of roots, reduced upon rainfall infiltration. At the end of the rainfall event, the bare soil lost all suction. For the vegetated soil with a relatively wide tree spacing (i.e. tests S120 and

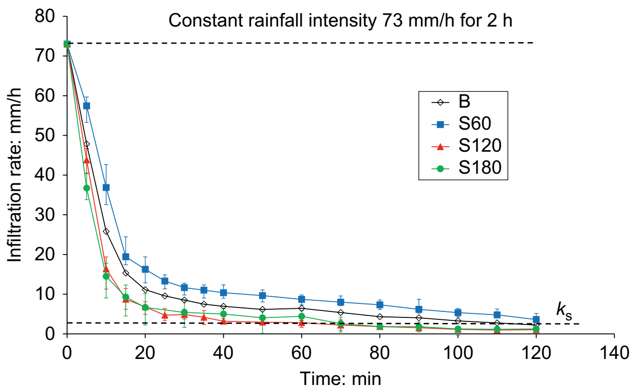

Fig. 9. Variations in infiltration rates with time for bare and vegetated soils

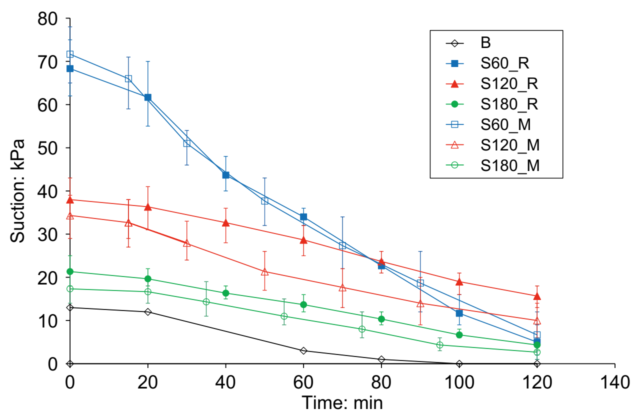

Fig. 10. Variations in suction at a depth of 50 mm with time for bare and vegetated soils during the applied 2-h rainfall event

S180), some suction (i.e. 3–18 kPa) was preserved along both arrays M and R, although the rate of suction reduction was similar to that for the bare soil. The two vegetated soils with these tree spacings were better able to retain suction because their infiltration rate was reduced (refer to Fig. 9), owing to the presence of roots and because of the relatively higher amount of evapotranspiration-induced suction before rainfall. When the tree seedlings were planted closer to each other at a spacing of 60 mm, the responses of suction were markedly different from those recorded for seedlings planted in the other two cases with wider spacings. Suction in the vegetated soil having 60 mm spacing of trees reduced much more rapidly as it had the highest infiltration rate among all cases (Fig. 9) and the amount of suction retained after rainfall was less than 12 kPa.

Figures 11(a)–11(d) show the vertical suction distribution before and right after the 2-h rainfall for the bare soil and the vegetated soils with the three different planting densities. After raining for 2 h, suction was reduced in the top 150 mm of the bare soil and only a minimal amount of suction (i.e. < 3 kPa) was preserved (Fig. 11(a)). On the contrary, with roots in the soil in tests S120 and S180 (Figs 11(b) and 11(c)), rainfall mainly affected the suction within the root zone. This means that, for a given period of rainfall, the depth of influence of suction in both vegetated soils was shallower than that in the bare soil. This observation is consistent with the test results shown in Fig. 9; that is, that the infiltration rate for the vegetated soil having the tree spacing of 120 or 180 mm was lower than that for the bare soil. For the tree spacing of 60 mm (Fig. 11(d)), the influence zone of suction was deeper, as suction changed not only within the root zone but also at a depth of 150 mm. This is likely to be attributable to the increased soil hydraulic conductivity associated with root decay, as indicated by the increased infiltration rate seen in Fig. 9.

In contrast, when inspecting the suction responses below the root zone at a greater depth of 250 mm in Fig. 11, suctions measured during the rainfall event were largely unchanged and preserved in all cases. The highest suction in the S60 samples (around 26 kPa) was the consequence of the more significant tree root-water uptake due to closer plant spacing (see Figs 6 and 7) before the rainfall happened.

DISCUSSION

In order to better understand the role of vegetation in the amount of suction retained during rainfall, water balance calculation was carried out using the instantaneous profiles of VWC depicted in Fig. 12. In each profile, the values of VWC at depths of 50 and 100 mm were obtained from the two soil moisture sensors (refer to Fig. 1), while those at depths of 150, 250 and 350 mm (i.e. below the root zone) were deduced by mapping the measured suctions to the wetting SWRC of the bare soil shown in Fig. 5(b). By considering mass continuity and the fact that no basal drainage was observed during the applied rainfall, and assuming one-dimensional water flow conditions in each test drum, the amount of water stored in tests B, S60, S120 and S180 at any time can be determined by integrating the VWC profiles. Fig. 13 shows that, in all cases, the total amount of water stored in the soil during the 2-h rainfall event was almost the same as the total amount of water infiltrated, as determined by the area bounded by each measured infiltration curve shown in Fig. 9. This suggests that, during the applied rainfall event, evaporation in the bare soil and evapotranspiration in the vegetated soil did not

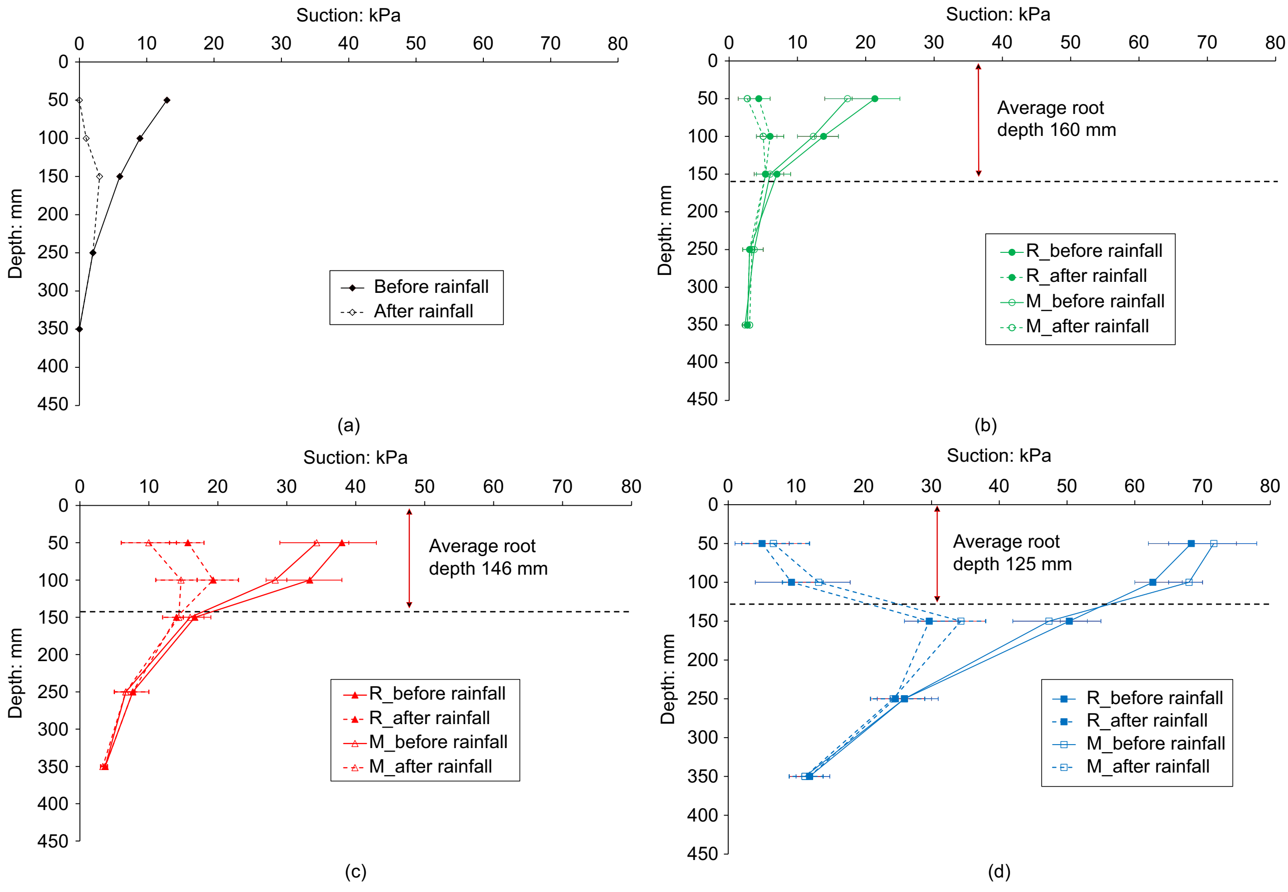

Fig. 11. Measured suction profiles before and after rainfall: (a) test B; (b) test S180; (c) test S120; (d) test S60

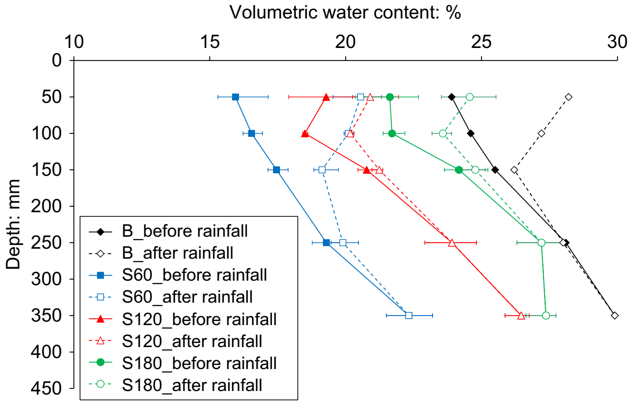

Fig. 12. Volumetric water content profiles of bare and vegetated soils before and after rainfall

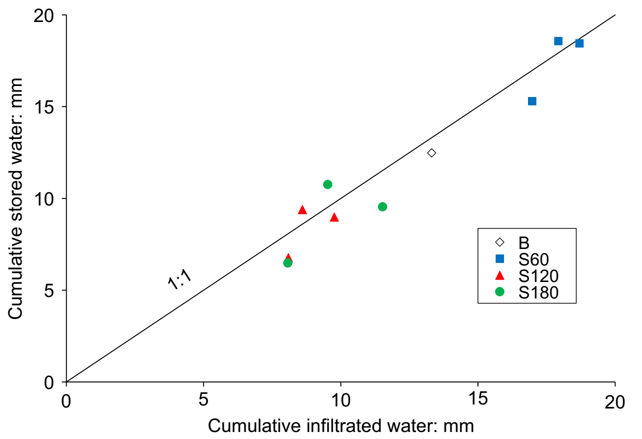

Fig. 13. Computed water balance in the bare and vegetated soils during 2-h rainfall

help to reduce the soil moisture very significantly, if at all. In fact, the PE and PET during the 2 h of rainfall were only 0·37 and 0·21 mm, respectively, and they were negligible compared to the total amount of water infiltration in each case (i.e. 8·1–18·7 mm). This means that the amount of transpiration during rainfall is much less than the amount of applied rainfall.

Although evapotranspiration of vegetated soil was likely to be minimal during the rainfall event, especially if the rain was short in duration, evapotranspiration could induce a significant amount of suction before rainfall (Figs 6–8). The different initial levels of suction before rainfall (hence different soil hydraulic conductivity; Ng & Menzies, 2007; Ng & Leung, 2012) may affect the suction responses during the subsequent rainfall. Fig. 14(a) shows the measured suctions before and after rainfall within the root zone (i.e. 50 mm and 100 mm) in all cases. For tree seedlings planted at the wider spacings of 120 and 180 mm, the higher the initial suction before rainfall, the larger the amount of suction retained after rainfall. Such a trend was consistently found in grass-covered ground (Lim *et al.*, 1996) and tree-covered ground with a plant spacing of 200 mm (Garg *et al.*, 2015b). Note that Garg *et al.* (2015b) tested in the field the same soil type and the same tree species as in the present study. This suggests that, as compared to the bare soil where only evaporation took place, evapotranspiration induced additional suction in CDG that was vegetated with tree seedlings at the spacings of 120 and 180 mm was more beneficial in preserving higher suction after rainfall.

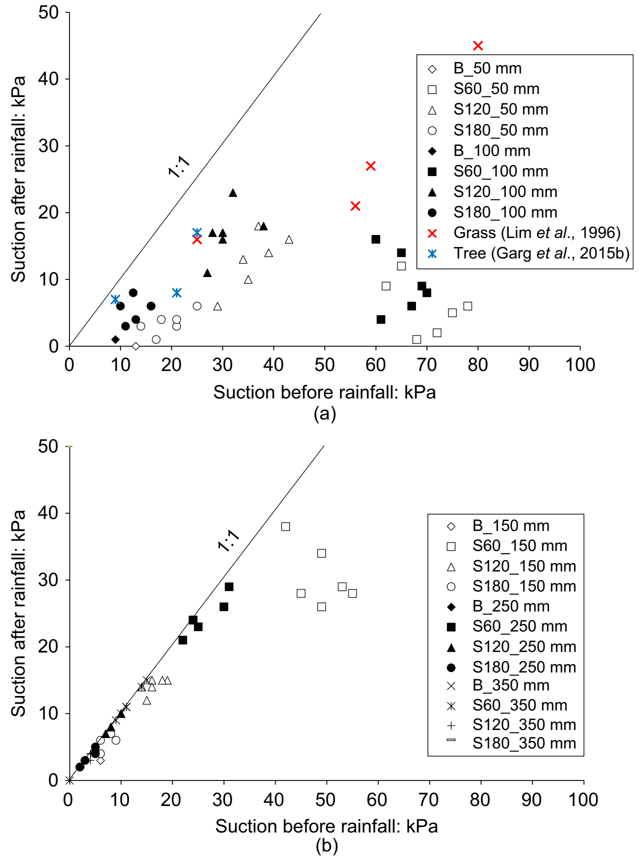

Fig. 14. Correlations of measured suction before and after rainfall at depths of: (a) 50 and 100 mm; (b) 150 mm, 250 mm and 350 mm

Interestingly, the data obtained from test S60 do not follow the same trend. Although the magnitude of evapotranspiration-induced suction before rainfall was the highest (Figs 6 and 8), the seedlings in this test preserved a relatively low amount of suction after rainfall (Fig. 14(a)). This suggests that, for this particular tree species grown in the CDG, the benefit of the additional suction induced by evapotranspiration within the root zone would be lost when the planting density is too high, as the resulting tree–tree competition would cause root decay (Fig. 3) and hence an increased rate of infiltration (Fig. 9).

Figure 14(b) shows the relationships of suction before and after rainfall at greater depths of 150, 250 and 350 mm. In most cases, except that for S60 samples at 150 mm depth, the suction induced by evapotranspiration before rainfall was largely preserved after rainfall. Although not all suctions were preserved in the S60 samples, the amount of suction after rainfall was the highest, when compared to other samples. Interestingly, this observation is opposite to the suction responses recorded in shallower depths within the root zone, where suction preserved in the S60 samples was relatively low (Fig. 14(a)). This highlights the importance of transpiration-induced suction and the associated extension of the suction influence zone before rainfall, as this suction is shown to control the amount of suction preserved during and after rainfall directly.

The laboratory findings in this study are particularly useful for field application at an initial stage of vegetation of engineered slopes/embankments, where young plant seedlings in a similar condition to that tested in this study (only one kind of plant species considered, i.e. non-mixed-species plantations) are usually transplanted. Based on the test data, it may be beneficial to apply a planting spacing of 60 mm for the young trees to enhance the shallow slope stability by preserving suctions at depths below the root zone. For the interaction between soil and semi-mature/mature vegetation, a number of field studies (Glendinning *et al.*, 2009; Rahardjo *et al.*, 2014; Smethurst *et al.*, 2015) have shown that, at one given planting density, some suction was maintained at depths below the root zone after rainfall, as similarly observed from this study. However, more research is needed to explore the effects of planting density of more mature vegetation on slope stability, over longer periods of time, as plants grow. It should be noted that an ideal planting spacing in slopes may depend on many factors, such as type of species to be planted and also potentially the slope angle. The recommendation of 60 mm spacing given in this paper is only relevant for the non-mixed-species planting condition and it should also be treated with caution when adopted for design directly.

SUMMARY AND CONCLUSIONS

This study explores the effects of planting density (i.e. 320, 81 and 36 tree seedlings/m^2; equivalent to plant spacings of 60, 120 and 180 mm) on the growth of a tree species, *S. heptaphylla*, and on induced suction in silty sand. Influences of planting density on soil water retention ability and infiltration rate were quantified to interpret the observed suction responses upon evapotranspiration and rainfall through water balance calculation. Three replicates were tested for each planting density to minimise any effects of tree variability. This involved testing 297 tree seedlings (only one plant species considered) in total.

It was revealed that the decrease in planting spacing from 180 mm to 60 mm reduced LAI from 1·35 to 0·96. The reduced growth was attributed to the increased competition among neighbouring trees for soil moisture, as indicated by the observed greater reduction in VWC when tree spacing was smaller. Owing to such tree–tree competition, the root systems were much more localised for all replicates in the case of 60 mm spacing than those where wider tree spacing was used. Reducing the tree spacing from 180 to 60 mm also led to a reduction in the total root volume by one-third and a decrease in mean root length by 22%. Evident root decay was observed for the case with the closest planting spacing of 60 mm.

When root decay presented (for the case of 60 mm spacing), the water retention ability of silty sand was reduced. In contrast, for the tree spacings of 120 and 180 mm, where mainly fresh roots were identified, the AEV of the silty sand increased to 4 kPa, indicating improved water retention ability. The size of the hysteresis loop for these two cases was markedly smaller than that for the previous case when silty sand contained a significant amount of decaying roots.

The highest planting density (i.e. closest spacing of 60 mm) induced the highest amount of suction (i.e. up to 75 kPa) and yielded the deepest zone of influence of suction, as compared to the other two cases with lower planting densities. This is attributed to the greater demand, and hence depletion, of soil moisture upon more significant tree–tree competition. As the tree spacing is 180 mm, effects of planting density vanished, because the amount of evapotranspiration-induced suction was found to be almost the same as that induced by one single tree.

Throughout a 2-h rainfall event, the infiltration rate for vegetated soil was always lower than that for bare soil by 18–58% when the trees were spaced relatively wide apart (i.e. 120 and 180 mm). Owing to the reduced infiltration rates, 3–18 kPa of suction was preserved (i.e. the top 100 mm depth) at the end of the rainfall in these two cases, whereas no suction was retained in the bare soil. In contrast, the presence of decaying roots in soil with the plant spacing of 60 mm meant that the infiltration rate was higher than that for the bare soil by at least 42%. The increased infiltration rate led to a rapid reduction in suction at shallow depths within the root zone and hence a small amount of suction retained (i.e. less than 12 kPa) within the root zone (i.e. top 100 mm). However, at greater depths below the root zone (i.e. up to a depth of 350 mm), suctions were largely preserved after the rainfall. The amount of suction preserved below the root zone was the highest for the soil with the closest plant spacing of 60 mm, because transpiration-induced suction before the rainfall event was the highest, when compared to other tree spacings.

ACKNOWLEDGEMENTS

The authors acknowledge research grant 2012CB719805 from the National Basic Research Program (973 Program) administered by the Ministry of Science and Technology of the People's Republic of China and research grants HKUST6/CRF/12R awarded by the Research Grants Council of the Government of the Hong Kong SAR. The third author would also like to acknowledge the EU Marie Curie Career Integration Grant under the project 'BioEPIC slope' and research travel support from the Northern Research Partnership (NRP).

NOTATION

D_{10} grain diameter at 10% passing
D_{30} grain diameter at 30% passing
D_{60} grain diameter at 60% passing
k_s saturated hydraulic conductivity
L planting spacing
m fitting parameter in van Genuchten's equation (van Genuchten, 1980)
n fitting parameter in van Genuchten's equation (van Genuchten, 1980)
α fitting parameter in van Genuchten's equation (van Genuchten, 1980)
θ_r residual volumetric water content
θ_s saturated volumetric water content

REFERENCES

Albalasmeh, A. A. (2013). *Biophysical controls on rhizosphere dynamics*. PhD thesis, University of California, Merced, CA, USA.

Allen, R. G., Pereira, L. S., Raes, D. & Smith, M. (1998). *Crop evapotranspiration: guidelines for computing crop water requirements*, Food and Agriculture Organization's Irrigation and Drainage paper no. 56. Rome, Italy: Food and Agriculture Organization.

ASTM (2010). Standard practice for classification of soils for engineering purposes (Unified Soil Classification System). West Conshohocken, PA, USA: American Society for Testing and Materials.

Azam-Ali, S. N., Gregory, P. J. & Monteith, J. L. (1984). Effects of planting density on water use and productivity of pearl millet (*Pennisetum typhoides*) grown on stored water: growth of roots and shoots. *Expl. Agric.* **20**, No. 3, 203–214.

Benomar, L., DesRochers, A. & Larocque, G. (2012). The effects of spacing on growth, morphology and biomass production and allocation in two hybrid poplar clones growing in the boreal region of Canada. *Trees – Struct. Funct.* **26**, No. 3, 939–949.

Beven, K. & Germann, P. (2013). Macropores and water flow in soils revisited. *Water Resources Res.* **49**, No. 6, 3071–3092.

Casper, B. B. & Jackson, R. B. (1997). Plant competition underground. *Annu. Rev. Ecol. Syst.* **28**, 545–570.

Darawsheh, M. K., Khah, E. M., Aivalakis, G., Chachalis, D. & Sallaku, F. (2009). Cotton row spacing and plant density cropping systems I. Effects on accumulation and partitioning

of dry mass and LAI. *J. Food Agric. Environ.* **7**, No. 3–4, 258–261.
Eastham, J., Rose, C. W., Charles-Edwards, D. A., Cameron, D. M. & Rance, S. J. (1990). Planting density effects on water use efficiency of trees and pasture in an agroforestry experiment. *New Zealand J. For. Sci.* **20**, No. 1, 39–53.
Farnham, D. E. (2001). Row spacing, plant density, and hybrid effects on corn grain yield and moisture. *Agron. J.* **93**, No. 5, 1049–1053.
Fatahi, B., Khabbaz, H. & Indraratna, B. (2010). Bioengineering ground improvement considering root water uptake model. *Ecol. Engng* **36**, No. 2, 222–229.
Francour, P. & Semroud, R. (1992). Calculation for the root area index in *Posidonia oceanica* in the Western Mediterranean. *Aquatic Bot.* **42**, No. 3, 281–286.
Garg, A., Leung, A. K. & Ng, C. W. W. (2015a). Comparisons of soil suction induced by evapotranspiration and transpiration of S. heptaphylla. *Can. Geotech. J.* **52**, No. 12, 2149–2155.
Garg, A., Coo, J. L. & Ng, C. W. W. (2015b). Field study on influence of root characteristics on soil suction distribution in slopes vegetated with *Cynodon dactylon* and *Schefflera heptaphylla*. *Earth Surf. Processes Landforms* **40**, No. 12, 1631–1643.
Gates, D. M. (1980). *Biophysical ecology.* New York, NY, USA: Springer-Verlag.
GCO (Geotechnical Control Office) (2000). *Geotechnical manual for slopes.* Hong Kong, China: Geotechnical Control Office.
GEO (Geotechnical Engineering Office) (2011). *Technical guidelines on landscape treatment for slopes.* Hong Kong, China: Geotechnical Engineering Office.
Ghestem, M., Sidle, R. C. & Stokes, A. (2011). The influence of plant root systems on subsurface flow: implications for slope stability. *Bioscience* **61**, No. 11, 869–879.
Glendinning, S., Loveridge, F., Starr-Keddle, R. E., Bransby, M. F. & Hughes, P. N. (2009). Role of vegetation in sustainability of infrastructure slopes. *Proc. Instn Civ. Engrs – Engng Sustainability* **162**, No. 2, 101–110.
Goldberg, D. E. & Miller, T. E. (1990). Effects of different resource additions on species diversity in an annual plant community. *Ecology* **71**, No. 1, 213–225.
Grayston, S. J., Vaughan, D. & Jones, D. (1997). Rhizosphere carbon flow in trees, in comparison with annual plants: the importance of root exudation and its impact on microbial activity and nutrient availability. *Appl. Soil Ecol.* **5**, No. 1, 29–56.
Green, D. S., Kruger, E. L., Stanosz, G. R. & Isebrands, J. G. (2001). Light-use efficiency of native and hybrid poplar genotypes at high levels of intracanopy competition. *Can. J. For. Res.* **31**, No. 6, 1030–1037.
Hau, B. C. H. & Corlett, R. T. (2003). Factors affecting the early survival and growth of native tree seedlings planted on a degraded hillside grassland in Hong Kong, China. *Restoration Ecol.* **11**, No. 4, 483–488.
Hillel, D. (1998). *Environmental soil physics.* San Diego, CA, USA: Academic Press.
Hunter, J. J. (1998). Plant spacing implications for grafted grapevine. I. Soil characteristics, root growth, dry matter partitioning, dry matter composition and soil utilisation. *S. Afr. J. Enol. Vitic.* **19**, 25–34.
Jiang, W. S., Wang, K. J., Wu, Q. P., Dong, S. T., Liu, P. & Zhang, J. W. (2013). Effects of narrow plant spacing on root distribution and physiological nitrogen use efficiency in summer maize. *Crop J.* **1**, No. 1, 77–83.
Krahn, J. & Fredlund, D. G. (1972). On total, matric and osmotic suction. *Soil Sci.* **114**, No. 5, 339–348.
Lam, C. C. & Leung, Y. K. (1995). *Extreme rainfall statistics and design rainstorm profiles at selected locations in Hong Kong*. Hong Kong: Royal Observatory.
Leung, A. K. & Ng, C. W. W. (2013). Analyses of groundwater flow and plant evapotranspiration in a vegetated soil slope. *Can. Geotech. J.* **50**, No. 12, 1204–1218.
Leung, A. K., Garg, A., Coo, J. L., Ng, C. W. W. & Hau, B. C. H. (2015a). Effects of the roots of *Cynodon dactylon* and *Shefflera heptaphylla* on water infiltration rate and soil hydraulic conductivity. *Hydrol. Processes* **29**, No. 15, 3342–3354.
Leung, A. K., Garg, A. & Ng, C. W. W. (2015b). Effects of plant roots on soil-water retention and induced suction in vegetated soil. *Engng Geol.* **193**, 183–197.
Lim, T. T., Rahardjo, H., Chang, M. F. & Fredlund, D. G. (1996). Effect of rainfall on matric suctions in a residual soil slope. *Can. Geotech. J.* **33**, No. 4, 618–628.
López, B., Sabaté, S. & Gracia, C. A. (2001). Vertical distribution of fine root density, length density, area index and mean diameter in a *Quercus ilex* forest. *Tree Physiol.* **21**, No. 8, 555–560.
Meek, B. D., Rechel, E. R., Carter, L. M., DeTar, W. R. & Urie, A. L. (1992). Infiltration rate of a sandy loam soil: effects of traffic, tillage, and plant roots. *Soil Sci. Soc. Am. J.* **56**, No. 3, 908–913.
Munns, R. & Sharp, R. E. (1993). Involvement of abscisic acid in controlling plant growth in soil of low water potential. *Aust. J. Plant Physiol.* **20**, No. 5, 425–437.
Ng, C. W. W. & Leung, A. K. (2012). Measurements of drying and wetting permeability functions using a new stress-controllable soil column. *J. Geotech. Geoenviron. Engng.* **138**, No. 1, 58–68.
Ng, C. W. W. & Menzies, B. (2007). *Advanced unsaturated soil mechanics and engineering*. London, UK: Taylor & Francis.
Ng, C. W. W., Leung, A. K. & Woon, K. X. (2014). Effects of soil density on grass-induced suction distributions in compacted soil subjected to rainfall. *Can. Geotech. J.* **51**, No. 3, 311–321.
Ng, C. W. W., Ni, J. J., Leung, A. K. & Wang, Z. J. (2016). A new and simple water retention model for root-permeated soils. *Géotechnique Lett.*, http://dx.doi.org/10.1680/jgele.15.00187.
Norton, J., Smith, J. & Firestone, M. (1990). Carbon flow in the rhizosphere of Ponderosa pine seedlings. *Soil Biol. Biochem.* **22**, No. 4, 449–455.
Penman, H. L. (1948). Natural evaporation from open water, bare soil and grass. *Proc. R. Soc. Lond.* **193**, No. 1032, 120–146.
Pinkard, E. & Neilsen, W. (2003). Crown and stand characteristics of Eucalyptus nitens in response to initial spacing: implication for thinning. *Forest Ecol. Managmt* **172**, No. 2–3, 215–227.
Rahardjo, H., Satyanaga, A., Leong, E. C., Santoso, V. A. & Ng, Y. S. (2014). Performance of an instrumented slope covered with shrubs and deep-rooted grass. *Soils Found.* **54**, No. 3, 417–425.
Rasband, W. S. (2011). *ImageJ.* Bethesda, MD, USA: US National Institutes of Health.
Sauer, D., Kuzyakov, Y. & Stahr, K. (2006). Spatial distribution of root exudates of five plant species as assessed by 14C labelling. *J. Plant Nutr. Soil Sci.* **169**, No. 3, 360–362.
Scanlan, C. A. & Hinz, C. (2010). Insight into the processes and effects of root induced changes to soil hydraulic properties. *Proceedings of the 19th world congress of soil science, soil solutions for a changing world*, Brisbane, Australia, vol. 2, pp. 41–44.
Scanlon, B. R., Reedy, R. C., Keese, K. E. & Dwyer, S. F. (2005). Evaluation of evapotranspirative covers for waste containment in arid and semiarid regions in the southwest USA. *Vadose Zone J.* **4**, No. 1, 55–71.
Scholl, P., Leitner, D., Kammerer, G., Lioskandl, W., Kaul, H. P. & Bodner, G. (2014). Root induced changes of effective 1D hydraulic properties in a soil column. *Plant Soil* **381**, No. 1–2, 193–213.
Sinnathamby, G., Phillips, D. H., Sivakumar, V. & Paksy, A. (2013). Landfill cap models under simulated climate change precipitation: impacts of cracks and root growth. *Géotechnique* **64**, No. 2, 95–107, http://dx.doi.org/10.1680/geot.12.P.140.
Smethurst, J. A., Clarke, D. & Powrie, W. (2006). Seasonal changes in pore water pressure in a grass covered cut slope in London Clay. *Géotechnique* **56**, No. 8, 523–537, http://dx.doi.org/10.1680/geot.2006.56.8.523.
Smethurst, J. A., Briggs, K. M., Powrie, W., Ridley, A. & Butcher, D. J. E. (2015). Mechanical and hydrological impacts of tree removal on a clay fill railway embankment. *Géotechnique* **65**, No. 11, 869–882, http://dx.doi.org/10.1680/geot.14.P.010.
Smucker, A. J. M., McBurney, S. L. & Srivastava, A. K. (1982). Quantitative separation of roots from compacted soil profiles by the hydropneumatic elutriation system. *Agron. J.* **74**, No. 3, 500–503.
TDOT (Tennessee Department of Transportation) (1981). *Subgrade construction and preparation: specifications for road and bridge construction*. Kingsport, TN, USA: Tennessee Department of Transportation (TDOT) Bureau of Highways.
Traoré, O., Groleau-Renaud, V., Plantureux, S., Tubeileh, A. & Boeuf-Tremblay, V. (2000). Effect of root mucilage and modelled

root exudates on soil structure. *Eur. J. Soil Sci.* **51**, No. 4, 575–581.

van Genuchten, M. T. (1980). A closed-form equation for predicting the hydraulic conductivity of unsaturated soils. *Soil Sci. Soc. Am. J.* **44**, No. 5, 892–898.

Veihmeyer, F. J. & Hendrickson, A. H. (1931). The moisture equivalent as a measure of the field capacity of soils. *Soil Sci.* **32**, No. 3, 181–193.

Wang, D., Kang, Y. & Wan, S. (2007). Effect of soil matric potential on tomato yield and water use under drip irrigation condition. *Agric. Water Managmt* **87**, No. 2, 180–186.

Watson, D. J. (1947). Comparative physiological studies on the growth of field crops: I. Variation in net assimilation rate and leaf area between species and varieties and within and between years. *Ann. Bot.* **11**, No. 1, 41–76.